Yao, E., Franke-Arnold, S. , Courtial, J. , Padgett, M.J. , and Barnett, S.M. (2006) Observation of quantum entanglement using spatial light modulators. Optics Express, 14 (26). pp. 13089-13094. ISSN 1094-4087

http://eprints.gla.ac.uk/28371/

Deposited on: 17th July 2012

Observation of quantum entanglement using spatial light modulators

Eric Yao, Sonja Franke-Arnold, Johannes Courtial and Miles J. Padgett

Department of Physics and Astronomy, SUPA, Kelvin Building, University of Glasgow, Glasgow, G12 8QQ, Scotland
e.yao@physics.gla.ac.uk

Stephen M. Barnett

Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, Scotland

Abstract: We use spatial light modulators to observe the quantum entanglement of down-converted photon pairs. Acting as diffractive optical elements within one of the beams, they can be reconfigured in real time to set the spatial profile of the measured mode. Such configurations are highly applicable to the measurement of orbital angular momentum states or other spatial modes, such as those associated with quantum imaging.

OCIS codes: (230.6120) Spatial light modulators; (999.9999) Optical vortices; (090.2890) Holographic optical elements; (270.0270) Quantum optics

---

References and links

1. A. Aspect, J. Dalibard and G Roger, " Experimental test of Bell inequalities using time-varying analysers," Phys. Rev. Lett. **49**, 1804-1807 (1982).
2. L. Mandel and E. Wolf, "Coherence and Quantum Optics" (Cambridge University Press, Cambridge, 1995).
3. D. V. Strekalov, A. V. Sergienko, D. N. Klyshko and Y.H. Shih, "Observation of 2-photon ghost interference and diffraction," Phys. Rev. Lett. **74**, 3600-3603 (1995).
4. J. C. Howell, R. S. Bennink, S. J. Bentley and R. W. Boyd, "Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion" Phys. Rev. Lett. **92**, 210403 (2004).
5. L. Allen, M. J. Padgett and M. Babiker, "The orbital angular momentum of light," Prog. Opt. **39**, 291-372 (1999)
6. L. Allen, S. M. Barnett and M. J. Padgett "Optical Angular Momentum" (Institute of Physics Publishing, Bristol, 2003).
7. A. Mair, A Vaziri, G Weihs and A. Zeilinger "Entanglement of the orbital angular momentum states of photons," Nature **412**, 313-316 (2001).
8. J. Leach, J. Courtial, K. Skeldon, S. M. Barnett, S. Franke-Arnold and M. J. Padgett, "Interferometric methods to measure orbital and spin or the total angular momentum of the photon," Phys. Rev. Lett. **92**, 013601 (2004).
9. M. A. Golub, E. L. Kaganov, A. A. Kondorov, V. A. Soifer, G. V. Usplen'ev, "Experimental investigation of a multibeam holographic optical element matched to Gauss-Laguerre modes," Kvantovaya Electronika **23**, 188-190 (1996).
10. G. Gibson, J. Courtial, M. J. Padgett, M. Vasnetsov, V. Pas'ko, S. M. Barnett and S. Franke-Arnold, "Free-space information transfer using light beams carrying orbital angular momentum," Opt. Express **12**, 5448-5456 (2004).
11. Yoshida, Narihiro, Toyoda, Haruyoshi, Igasaki, Yasuhiro, Mukohzaka, Naohisa, Kobayashi, Yuji, Hara and Tsutomu "Nonpixellated electrically addressed spatial light modulator (SLM) combining an optically addressed SLM with a CRT" Proc. SPIE **2885** 132-136 (1996)
12. J. Leach, M. Dennis, J. Courtial and M. Padgett, "Knotted threads of darkness," Nature **432**, 165 (2004).
13. J. Leach, M. R. Dennis, J. Courtial and M. J. Padgett, Vortex knots in light", New J. Phys. **7**, 55.1-55.11 (2005).
14. V. Yu. Bazhenov, M. V. Vasnetsov and M. S. Soskin, "Laser beams with screw dislocations in their wavefronts," JETP Lett. 52, 429–431 (1990).
15. S. Franke-Arnold and S. M. Barnett, M. J. Padgett and L. Allen, "Two-photon entanglement of orbital angular momentum states," Phys. Rev. A **65**, 033823 (2002).

#76316 - $15.00 USD Received 24 October 2006; revised 14 December 2006; accepted 16 December 2006

16. A. Vaziri, G. Weihs and A. Zeilinger, "Superpositions of the orbital angular momentum for applications in quantum experiments," J. Opt. B: Quantum Semiclass. Opt. **4** S47–S51 (2002).
17. M. Padgett, J. Courtial, L. Allen, S. Franke-Arnold and S. M. Barnett, "Entanglement of orbital angular momentum for the signal and idler beams in parametric down-conversion," J. Mod. Opt. **49**, 777-785 (2002).
18. A. Vaziri, G. Weihs and A. Zeilinger, "Experimental Two-Photon, Three-Dimensional Entanglement for Quantum Communication," Phys. Rev. Lett. **89**, 240401 (2002).
19. R. Ghosh, C. K. Hong, Z. Y. Ou and L. Mandel, "Interference of two photons in parametric down conversion," Phys. Rev. A **34**, 3962–3968 (1986).
20. S. Franke-Arnold, S. M. Barnett, E. Yao, J. Leach, J. Courtial and M. Padgett, "Uncertainty principle for angular position and angular momentum", New J. Phys. **6**, 103.1-103.8 (2004).
21. D. T. Pegg, S. M. Barnett, R. Zambrini, S. Franke-Arnold and M. Padgett, "Minimum uncertainty states of angular momentum and angular position" New J. Phys. **7**, 62.1-62.20 (2005).
22. J. B. Götte, S. Franke-Arnold and S. M. Barnett "Angular EPR paradox" J. Mod. Opt. **53**, 627-645 (2006).
23. S. M. Barnett and R. Zambrini, *Orbital angular momentum of light,* in Quantum Images, ed. M. Kolobov (Springer-Verlag, in press).

1. Introduction

In the early 1980s Aspect *et al.* famously demonstrated the non-local nature of quantum mechanics as applied to correlations in the measured polarization states of photon pairs produced in a spontaneous emission cascade [1]. This phenomenon of non-locality is, of course, the characteristic property associated with entanglement. More recent experiments have exploited the photon pairs generated in parametric down-conversion where phase matching naturally induces entanglement between the wavevectors of the photon pairs [2]. The experiments of Aspect *et al.* demonstrated entanglement by measuring correlations between non-orthogonal polarizations, but entanglement has also been demonstrated for a variety of other degrees of freedom. These experiments include measuring the transverse position of one photon and the linear momentum of its partner by placing a diffraction slit in one of the beams and observing the coincidently detected photons in the other beam. The result of this "ghost diffraction" experiment is the observation of the slit diffraction pattern in the beam that does not contain the slits [3]. More recently, the entanglement between position and momentum has been observed in an experimental realization of the original Einstein Podolsky Rosen (EPR) paradox [4].

The polarization state of light is a manifestation of the spin angular momentum of the photon. It is well-known that light also possesses an orbital angular momentum (OAM) which is manifest in the phase structure of the beam [5,6]. In 2001 Zeilinger *et al.* reported correlation in the measured orbital angular momentum states of down-converted photon pairs [7], demonstrating that, as with polarization or spin angular momentum, the orbital angular momentum of light is a quantum variable associated with single photons.

Single photon detectors can be combined with efficient polarizers to give a high quantum efficiency (QE) for the measurement of polarization states, but the efficient measurement of orbital angular momentum is not so straightforward. Although both orbital and spin angular momentum can be measured interferometrically [8], extension of the technique to cover many possible orbital angular momentum states is complicated. Alternatively, orbital angular momentum states can be measured using diffractive optics (holograms) to selectively couple a specific OAM state into single-mode fiber, with a range of different OAM states tested by sequentially inserting the appropriate hologram. Holograms can also be designed to test for a fixed number of states [9] but with QE inherently limited to be no better than the reciprocal of the number of different states considered [10].

Spatial Light modulators (SLMs) are liquid crystal devices that can be addressed to produce a spatially dependent phase delay on a reflected or transmitted beam [11]. With video resolution and refresh rates, they are frequently employed as reconfigurable holograms in various beam-shaping applications. They are primarily used as phase modulators, but the phase pattern can be calculated to give both phase and intensity control of the diffracted light

[12,13]. A key advantage of using SLMs to implement holograms is that they can be precisely updated without any need to realign the optical system. For the experiments demonstrating entanglement of OAM states [7], the holograms were static. Measuring differing quantum states, in this case, required careful interchange and realignment between different holograms, and the detection of different superposition of OAM states required manual shifting of the holograms. In the present work we demonstrate that the fixed holograms can be replaced with SLMs which can be reconfigured easily and rapidly. This allows us to examine the behavior of the coincidence count rate as the spatial mode is changed. We apply this technique to observe entanglement in both angular and linear momentum states.

2. Experimental configuration

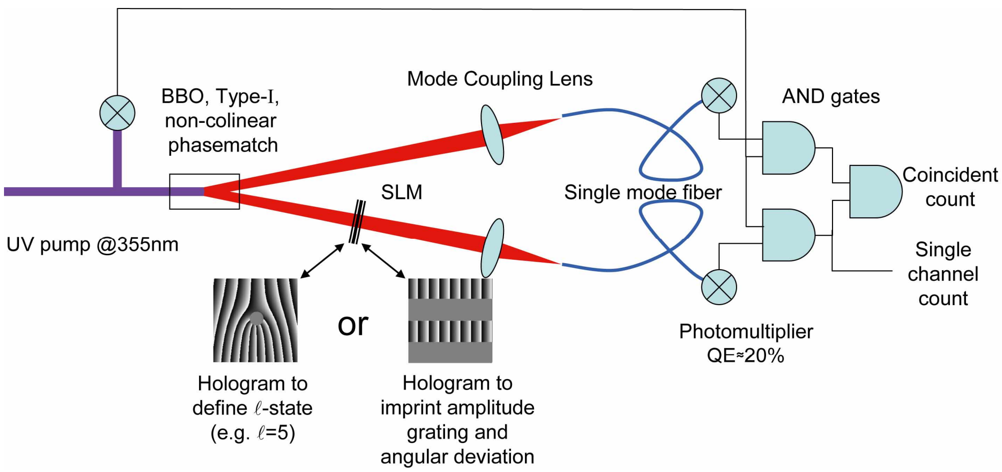

Fig. 1. Experimental configuration for optical demonstration of quantum entanglement between photon pairs arising from parametric down-conversion. The key component for manipulating the detected photon state is a programmable spatial light modulator.

The experimental setup is shown in Fig. 1. Our down-conversion source is based on a Q-switched frequency-tripled YAG laser that produces 50ns duration pulses at 150kHz, with an average power up to 60mW. The output beam, which is spatially filtered and collimated to a diameter of 200µm, is incident on a 2mm long BBO crystal, cut for frequency-degenerate, Type-I, non-colinear phase matching with a semi-cone angle for the signal and idler beams of 4°. At a distance of 1m from the crystal, 30mm focal length lenses couple the down-converted light into single-mode fibers that, in turn, are coupled to photomultipliers with single-photon sensitivity (QE ≈ 20%). The TTL (5 volts) outputs from each of the photomultipliers are subject to a logical AND operation against the synchronous TTL pump trigger. This results in a single channel count rate of ≈150/sec and reduces the dark count rate to ≈1/sec. These conditioned signals are subjected to a further logical AND operation, giving a coincidence count rate of up to 5/sec and a dark coincidence count rate of ≈0.01/sec. All the AND gates are implemented using standard high-speed electronics. The count rates of the two individual channels along with the coincidence count rate are read using a counter/timer interface board and recorded. An SLM is inserted into one of the two arms, approximately at a conjugate plane to the fiber facet. If the SLM is addressed with a standard diffraction grating, then the resulting angular deviation is equivalent to a lateral displacement of the fiber facet. The SLM can be addressed to include a helical phase term $\exp(i\ell\phi)$ which, when combined with an angular deviation, gives the characteristic ℓ-forked hologram frequently encountered in OAM studies [14]. The area of uniform phase at the centre of the hologram gives a better intensity match to the desired mode [13]. When the SLM is addressed in this way, the detected mode corresponds to a helically phased beam with an azimuthal phase term

#76316 - $15.00 USD Received 24 October 2006; revised 14 December 2006; accepted 16 December 2006

$\exp(i\ell\phi)$ and hence an orbital angular momentum of $\ell\hbar$ per photon, see section 3. Alternatively, if the angular deviation is varied, this effectively allows the coincidence count rate to be measured as a function of the lateral displacement of the two fibers. Here, the hologram is acting both as a diffraction grating (horizontal stripes) and providing the angular scan (rotation of the vertical stripes), see section 4.

3. Entanglement of orbital angular momentum states

It is now well established that angular momentum is conserved in parametric down-conversion at the single photon level. This has been demonstrated in experiment [7] and proven, theoretically, to be a strict consequence of phase-matching [15]. This means that in parametric down-conversion a high coincidence count rate should be observed when the orbital angular momenta of the pump (0) and down-converted beams (1,2) are related by

$$\hbar\ell_0 = \hbar\ell_1 + \hbar\ell_2$$
$$\Rightarrow \ell_0 = \ell_1 + \ell_2 .$$

Equivalently, the phase matching can be understood as a relationship between the phases of the three waves in the transverse (*x*,*y*) plane:

$$\Phi_0(x,y) = \Phi_1(x,y) + \Phi_2(x,y) - \frac{\pi}{2}.$$

Great care needs to be taken, when measuring angular momenta with $\ell \neq 0$, to ensure that the fork axis of the hologram is accurately aligned with the detection axis of the fiber. Any lateral shift in the position of the hologram means that the detected mode will be a superposition of different ℓ-states and this will be reflected in the measured coincidence rate [7, 16, 17]. This phenomenon has been exploited to look for higher dimensional entanglement of OAM states [18], but requires careful and repeatable positioning of the holograms.

In our experiment we investigate entanglement for both OAM and linear momentum states where the mode defining element is a SLM. We measure the correlation between photons in the $\ell = 0$ mode in one arm and another mode defined by the SLM in the other arm. Figure 2 shows our measured ratio between the coincident count rate and the single (SLM) channel count-rate, as a function of a lateral (*x*, *y*) shift of the fork axes of the ($\ell_{\mathrm{SLM}} = -2,-1,...,+2$) holograms. Acquisition of these images required no intervention or alignment of any sort, but merely re-addressing the SLM. When the hologram axis is aligned with the beam axis then, as expected, the coincident count is zero unless $\ell_{\mathrm{SLM}} = 0$. The drop in the coincidence count rate by more than two orders of magnitude observed for $\ell_{\mathrm{SLM}} \neq 0$ confirms correlation in the OAM of the down-converted photons. Note that because of the corresponding mode size, the dip in the coincidence count for $\ell_{\mathrm{SLM}} = \pm 2$ is wider than for $\ell_{\mathrm{SLM}} = \pm 1$. We use the position of these dips to optimise alignment of the optical axis of the hologram for subsequent experiments.

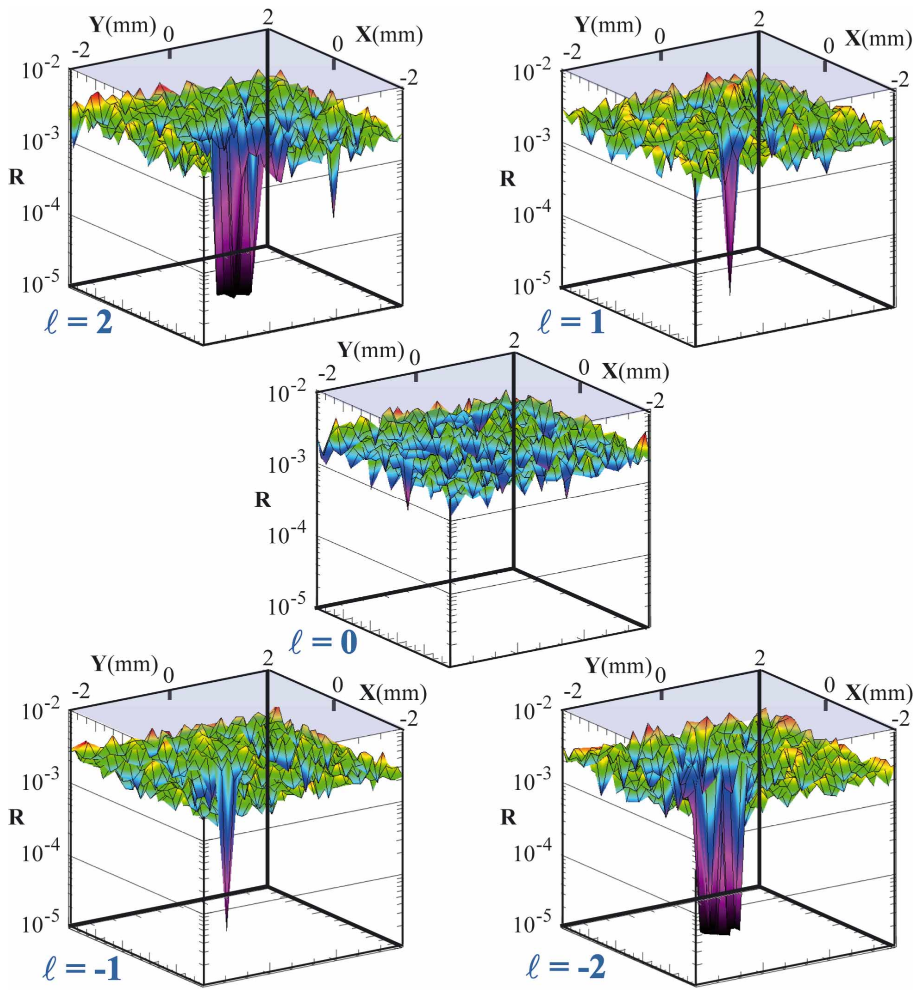

Fig. 2. The measured ratio, **R**, between coincidence and single channel count rate as a function of lateral displacement of the various holograms, displayed as logarithmic surface plots.

4. Entanglement of linear momentum states

One of the most striking illustrations of quantum entanglement is "ghost-diffraction" [3]. In the classical regime, the light emitted by parametric down-conversion is spatially incoherent [19] meaning that when a grating is placed in the beam, no diffraction pattern will be observed. For quantum entangled photons there is a fixed phase relationship between the pump and the down-converted beams. This means that if the pump is spatially coherent then the measurement of a spatially coherent mode in one of the down-converted beams, if detected in coincidence, defines a spatially coherent mode in the other beam. Consequently, if a grating is placed in one beam and a spatially coherent state (e.g. as transmitted by single mode-fiber) is measured, then scanning the angular position of the other detector will result in the diffraction pattern being observed in the coincident count rate.

In our experiment the angular scanning of one of the detection arms and introduction of a grating can readily be implemented using the SLM. Figure 3 shows the measured coincidence count rate and single channel count rate for the beam containing the SLM, as a function of the angular deviation between the channels. Note that the characteristic fringe pattern associated with the grating is only present in the coincidence channel. The destructive interference

#76316 - $15.00 USD Received 24 October 2006; revised 14 December 2006; accepted 16 December 2006

leading to minima in the coincidence count rate is an indication of quantum interference and is a consequence of the entanglement of the photon pairs.

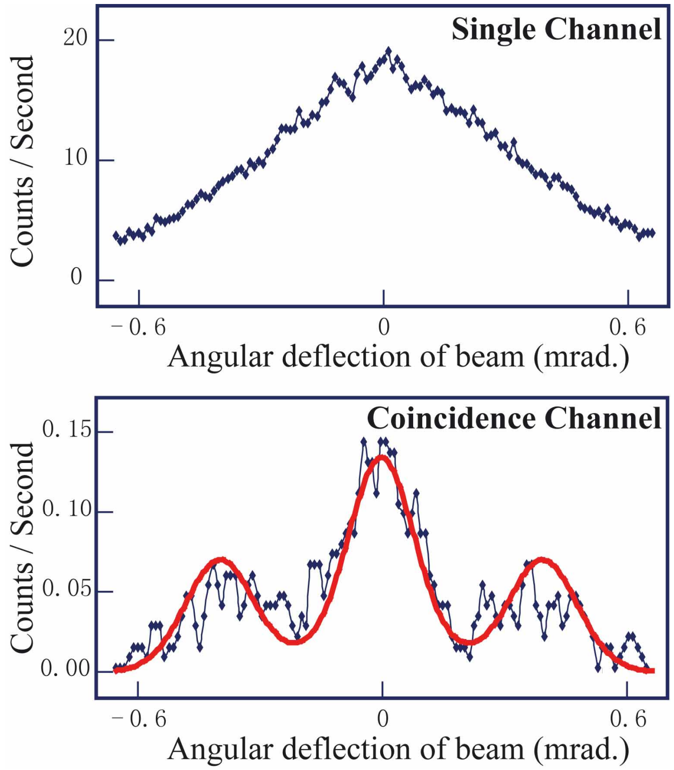

Fig. 3. The measured single channel and coincidence channel count rate as a function of angular deviation of the light beam introduced by the hologram. While the graph for the single channel count shows no interference fringes, these are observed in the coincidence channel. The red line is the expected interference fringe pattern.

5. Discussion and conclusions

We have shown that SLMs can be used as key components within quantum optics experiments and, in particular, for the observation of entanglement between the spatial modes of down-converted beams. The main advantage of a SLM is that it can be reconfigured without affecting the alignment of the apparatus. We have demonstrated the use SLMs in observing the correlation of OAM states and in ghost diffraction experiments arising from the entanglement of linear momentum and linear position. The former raises the possibility for new experiments investigating the angular form of the Heisenberg uncertainty principle [20,21] and of demonstrating an angular version of the EPR paradox [22]. The latter has clear applications for the study of quantum imaging [23].

Acknowledgments

This work is supported by EPSRC and SFA and JC acknowledge support by the Royal Society.